Comparison of H-minus and Proton Beam Heating in Thin Foils

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Introduction

When a H^- beam enters a thin foil or a wire scanner wire, the two loosely bound atomic electrons (valence electrons) quickly detach from the proton, resulting in three independent charged particles, each contributing to the dE/dx heating in the foil. For wire scanner wires, this results in a significantly higher peak temperature of the wire. Because the range-energy relation for electrons is significantly different than that for protons, the foil or wire heating by a H^- beam has a different energy dependence than the standard energy dependence for proton beams, which is based on the Bethe-Bloch equation.

The purpose of this note is to determine the energy dependence of the foil heating by a H^- beam, compared to a proton beam.

For a 10 MeV H^- beam, the two valence electrons are each about 5.4 keV. This energy is completely negligible compared to the proton dE/dx heating in a 1-mil (25 micron) tungsten foil (about 960 keV), even if both valence electrons completely stop in the foil. However, for a 1000-MeV H^- beam, the valence electrons are each 544 keV, which is significantly more than the proton dE/dx heating in a 1-mil tungsten foil (about 60 keV). In this case most of the heating is caused by the valence electrons, even if they do not stop in the foil.

dE/dx for protons

For thin foils, the standard Bethe-Bloch relation for dE/dx is used. The algorithm is essentially the one appearing in the range-energy tables published by Barkas and Berger [1]. It is assumed here that the proton dE/dx does not change as it passes through the foil. This approximation is satisfactory for proton energies above 10 MeV, and foils less than 100 microns thick.

The dE/dx energy loss is an interaction between the primary proton and electrons in the foil. The proton can also interact with the nuclei in the foil. The probability of this is very small, however. A 4-mil tungsten foil is about 0.19 grams per cm^2. This is only about 0.15% of a nuclear interaction length. Coulomb (multiple) scattering on the nucleus does not contribute to foil heating, because the energy transfer is small.

Range-energy for electrons

The initial velocity for the valence electrons in the foil is the same as that for the proton, but decreases very quickly as the electrons lose energy. Furthermore, the electron range is not well defined due to a combination of energy straggling, scattering, and other energy-loss mechanisms (e.g., bremsstrahlung and x-rays). In this paper, an empirical range energy relation (sometimes called Feather's Rule) for electrons in aluminum is used[2]. To extrapolate from aluminum to other materials, this range-energy relation is corrected only for Z and A.

The range-energy relation used for the valence electrons is

$$R = \frac{13 \cdot A}{27 \cdot Z} E^n \quad \text{milligrams per cm}^2 \tag{1}$$

where

$$n = 1.265 - 0.0954 \cdot Ln(E) \tag{2}$$

and E is the electron energy in MeV.

Result for tungsten foils

Figure 1 shows a plot of the total energy loss of a proton and a H^- particle in a 1-mil tungsten foil, as a function of beam energy. As predicted, below 10 MeV, the contribution of the valence electrons to the total H^- energy loss is negligible. The significant peak at about 350 MeV is due the two valence electrons, each about 190 keV, which just barely stop in the foil. For comparison, the proton energy loss is only 80 keV. The peak is due to the very nonlinear dependence of range on energy.

Above 350 MeV, the valence electrons begin exiting the foil, and have a lower energy loss rate (the derivative of the above range energy relation). Below 350 MeV, the valence electrons dissipate their entire kinetic energy (which is proportional to the H^- energy) in the foil.

The vertical scale is in units of MeV per particle, which is the same as MJ (megaJoules) per Coulomb of beam.

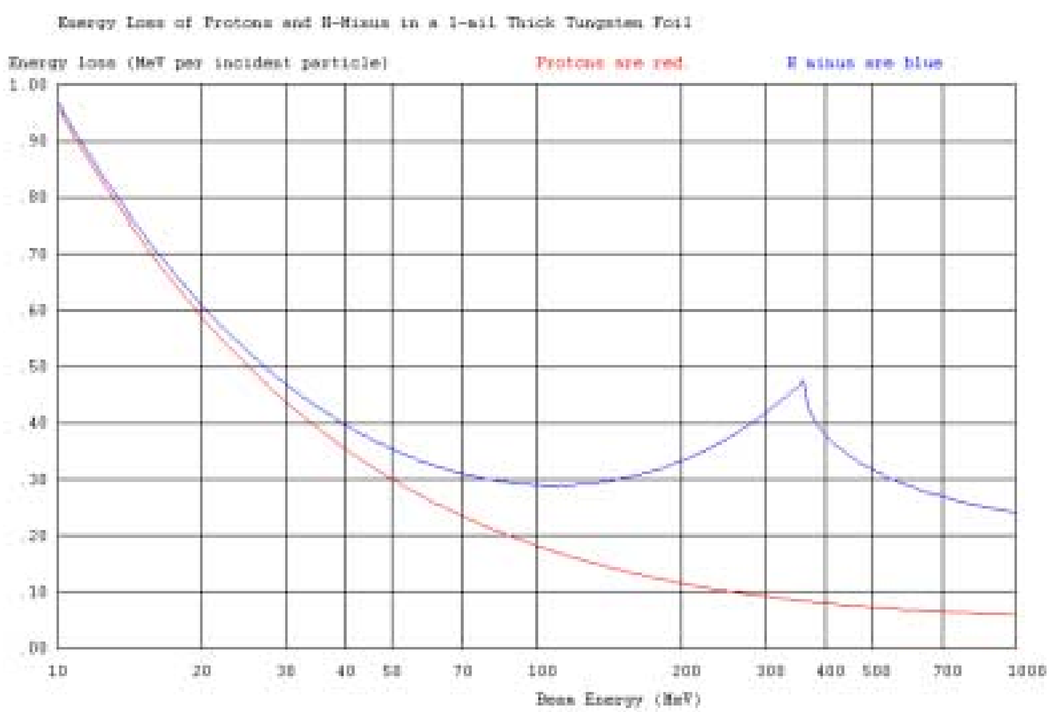

Figure 1. Energy loss vs. beam energy for H^- and protons in a 1-mil tungsten foil.

Because of electron energy and range straggling, the pronounced peak at 350 MeV will be washed out for the real case. In addition, for a thin wire, the wire thickness varies from zero to the full diameter, with an average thickness of 0.785*diameter, which will further wash out this structure.

Figure 2 is the same as Figure 1, except that the foil is now 4 mils (100 microns) thick. Note that the energy loss at 10 MeV has scaled linearly with thickness, but the energy of the peak in the electron energy deposition has moved from 350 MeV to nearly 1000 MeV.

Figure 2. Same as Figure 1, except that the tungsten foil is 4 mils thick.

<u>Niobium foils</u>

Figure 3 shows the energy loss vs. energy for protons and H^- in a 1-mil niobium foil. The vertical scale is the same as for Figure 1 (1-mil tungsten). The energy loss is lower primarily because of the lower density (8.57 vs. 19.3). Note also that because of the lower density, the peak has moved from 350 MeV to about 230 MeV.

Figure 4 shows the results for a 4-mil niobium foil. Compare these results to Figure 2 for a 4-mil tungsten foil.

<u>Carbon (graphite) foils</u>

Figures 5 and 6 show the results for 1-mil and 4-mil thick carbon (graphite) foils. Compare to Figures 1 through 4. The very low density of graphite has reduced the energy loss by nearly the ratio of densities.

<u>Conclusion</u>

The foil heating by an H^- beam is significantly higher than the heating by a proton beam at energies exceeding 10 MeV, but not below 10 MeV, where the contribution of the two valence electrons is negligible.

<u>References</u>

[1] Barkas and Berger, "Tables of Energy Losses and ranges of heavy Charged Particles", NASA report # NASA SP-3013 (1964).

[2] Evans, “The Atomic Nucleus”, pages 624-625, McGraw Hill (1955).

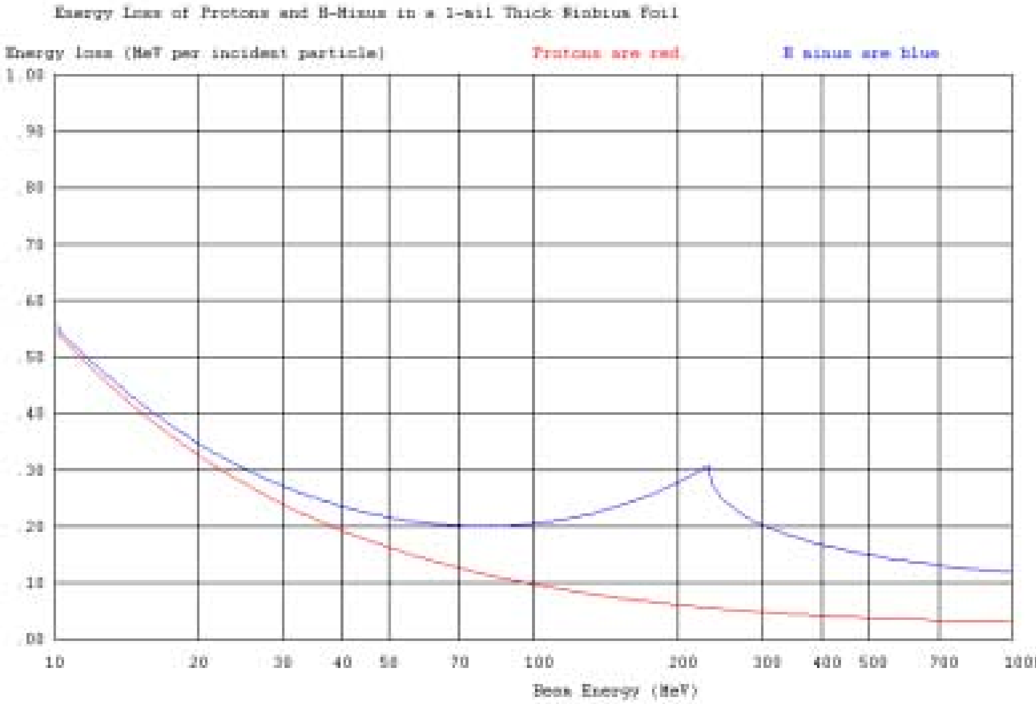

Figure 3. Energy loss vs. beam energy for H^- and protons in a 1-mil niobium foil.

Figure 4. Energy loss vs. beam energy for H^- and protons in a 4-mil niobium foil.

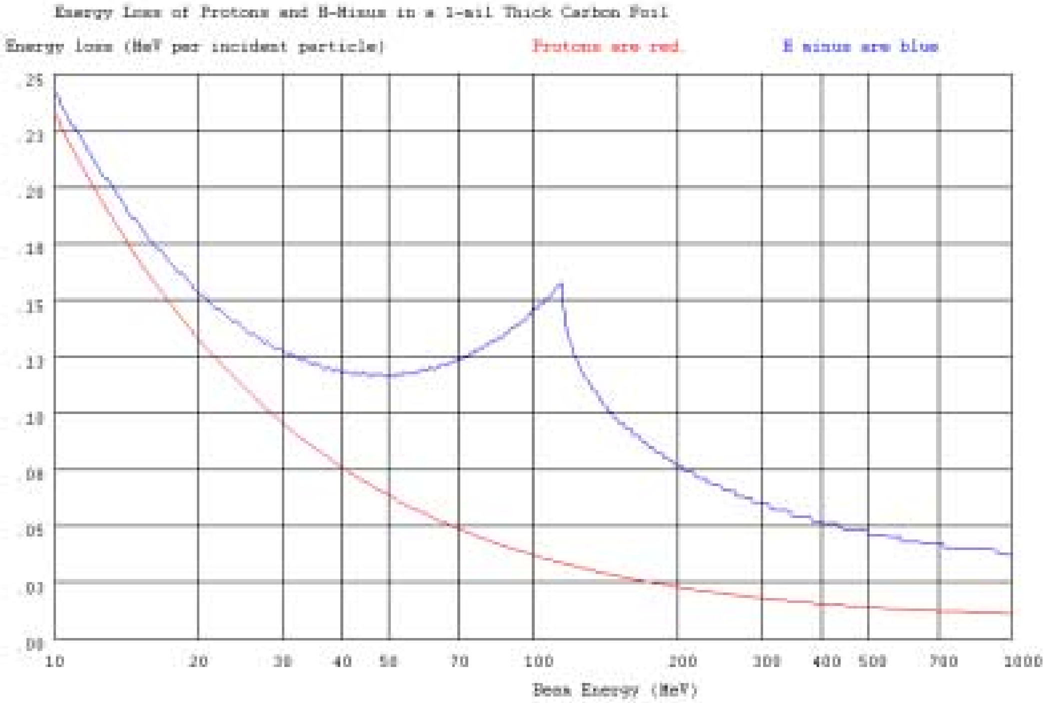

Figure 5. Energy loss vs. beam energy for H^- and protons in a 1-mil graphite foil.

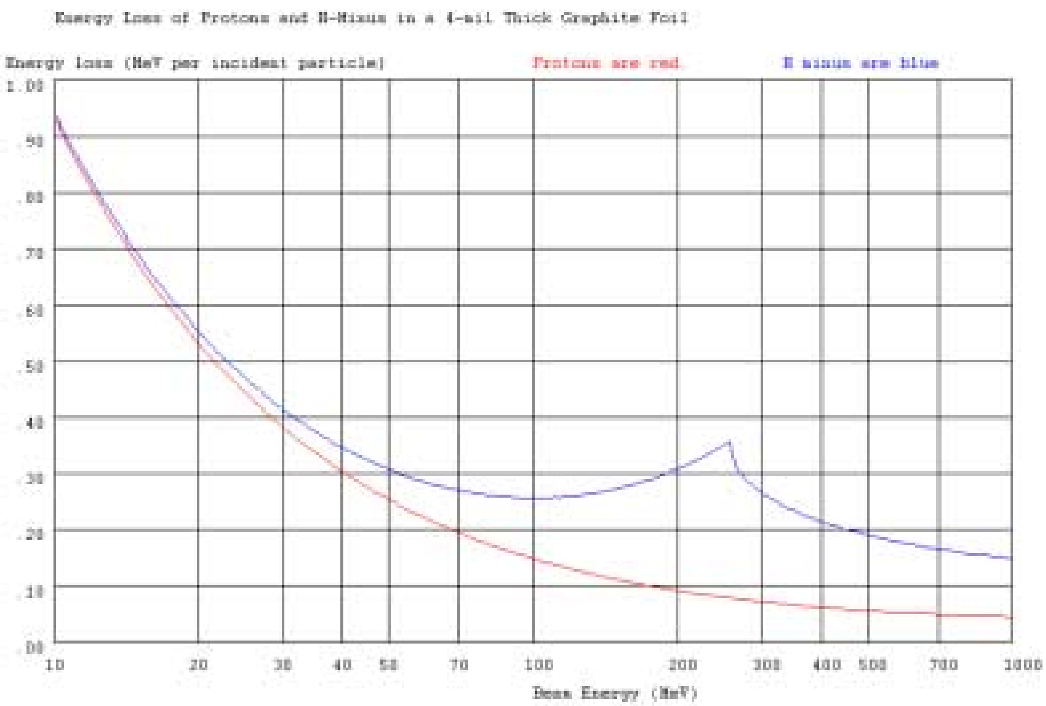

Figure 6. Energy loss vs. beam energy for H^- and protons in a 4-mil graphite foil.